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Social network analysis as a tool for marine spatial planning: Impacts of decommissioning on connectivity in the North Sea

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Abstract

1. Connectivity of marine populations and ecosystems is crucial to maintaining and enhancing their structure, distribution, persistence, resilience and productivity. Artificial hard substrate, such as that associated with oil and gas platforms, provides settlement opportunities for species adapted to hard substrates in areas of soft sediment. The contribution of artificial hard substrate and the consequences of its removal (e.g. through decommissioning) to marine connectivity is not clear, yet such information is vital to inform marine spatial planning and future policy decisions on the use and protection of marine resources.
2. This study demonstrates the application of a social network analysis approach to quantify and describe the ecological connectivity, informed by particle tracking model outputs, of hard substrate marine communities in the North Sea. Through comparison of networks with and without artificial hard substrate, and based on hypothetical decommissioning scenarios, this study provides insight into the contribution of artificial hard substrate, and the consequence of decommissioning, to the structure and function of marine community connectivity.
3. This study highlights that artificial hard substrate, despite providing only a small proportion of the total area of hard substrate, increases the geographic extent and connectivity of the hard substrate network, bridging gaps, thereby providing 'stepping stones' between otherwise disconnected areas of natural hard substrate. Compared to the baseline scenario, a decommissioning scenario with full removal of oil and gas platforms results in a nearly 60% reduction in connectivity. Such reduction in connectivity may have negative implications for species' distribution, gene flow and resilience following disturbance or exploitation of marine hard substrate communities.
4. *Synthesis and applications*. Social network analysis can provide valuable insight into connectivity between marine communities and enable the evaluation of impacts associated with changes to the marine environment. Providing standardized, transparent and robust outputs, such a tool is useful to facilitate understanding

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across different disciplines, including marine science, marine spatial planning and marine policy. Social network analysis therefore has great potential to address current knowledge gaps with respect to marine connectivity and crucially facilitate assessment of the impacts of changes in offshore substrate as part of the marine spatial planning process, thereby informing policy and marine management decisions.

KEYWORDS

artificial hard substrate, connectivity, decommissioning, marine management, marine spatial planning, offshore energy, particle tracking, social network analysis

1 | INTRODUCTION

The marine environment is under increasing pressure globally from human activities, such as aquaculture, fisheries, recreational use and offshore energy (Rees, 2012). Effective management is crucial to balance the economic, biological and social benefits of the marine environment, and as presented in UN sustainable development goal 14 (UNCSD or ‘Rio+20’), achieve ‘sustainable use and conservation of the oceans’. Marine spatial planning (MSP), relating to different human activities, provides a framework which facilitates optimal and sustainable use of the marine environment whilst reducing conflict between stakeholders (Stelzenmüller et al., 2013). Four main ecological principles (a) maintenance of native species diversity, (b) habitat diversity and heterogeneity, (c) key species and (d) connectivity have been identified to guide MSP (Foley et al., 2010).

Connectivity refers to the exchange of individuals between populations, communities and ecosystems, and is fundamental to the persistence, recovery, structure, distribution and productivity of marine life (Balbar & Metaxas, 2019; Carr et al., 2017). Population ‘openness’, where replenishment by immigration is possible, has been shown to facilitate rapid and successful recovery of populations following disturbance or exploitation (Pinsky, Palumbi, Andréfouët, & Purkis, 2012). There are a number of mechanisms by which connectivity may occur. These include the movement of mobile adult organisms, migration of juveniles and, crucial for benthic species, dispersal of pelagic larvae via ocean currents (Cowen & Sponaugle, 2009). However, despite such importance, knowledge and understanding of connectivity remains limited, and its consideration in marine spatial planning is rare (Bray, Kassis, & Hall-Spencer, 2017).

The industrial exploitation of energy resources in the North Sea, which started as early as the 1960s with the oil and gas industry, and more recently the harvesting of wind power, has led to the installation of many offshore structures, with more than 500 platforms associated with oil and gas (Fujii & Jamieson, 2016) and more than 2,500 offshore wind turbines to date (https://northsearegion.eu/northsee/e-energy/offshore-renewable-energy-developments-offshore-wind/). In combination with associated infrastructure, such as cables and pipelines, and additional structures such as shipwrecks, these platforms create discrete areas of artificial hard substrate, often within large expanses of soft sediment. By providing hard substrate habitat in an otherwise open-water, sedimentary environment, offshore structures attract benthic and pelagic marine life (Coates, Deschutter, Vincx, & Vanaverbeke, 2014; Reubens et al., 2013; Wilhelmsson & Malm, 2008; Wilhelmsson, Malm, & Ohman, 2006). Over time they may function as multiple reef-like features (Bergmark & Jørgensen, 2014; Bergström et al., 2014; Consoli, Mangano, Sarà, Romeo, & Andaloro, 2018; Consoli, Romeo, Ferraro, Sarà, & Andaloro, 2013; Fujii, 2015; Lokkeborg, Humborstad, Jørgensen, & Soldal, 2002; Neira, 2005; Vold Soldal, Svellingen, Jørgensen, & Løkkeborg, 2002; Whomersley & Picken, 2003) enhancing foraging or refuge, and creating opportunities for new trophic links in the local ecosystem (Raoux et al., 2017; Ronconi, Allard, & Taylor, 2015; Wilhelmsson et al., 2006).

The MSP process is particularly important in the North Sea where several countries have jurisdictional boundaries and, in particular, in the southern North Sea, where additional offshore wind turbine installations are planned. At present, each nation's legislation is set within the bounds of European Union Directives, which aim to protect marine ecosystems and minimize significant impacts within a context of renewable energy and sustainable growth (i.e. Marine Strategy Framework Directive, Environmental Impact Directive and Marine Spatial Planning Directive respectively). Under the OSPAR Convention, the North Sea marine environment (as part of the North east Atlantic) is also protected from human activities adversely impacting biodiversity and the ecosystem.

Environmental impacts can arise during installation, operation and decommissioning of energy-related structures (Gill et al., 2018). Decommissioning, which is stipulated in the licenses granted (e.g. OSPAR, 1998; UNICLOS, 1982; UK Energy Act, 2008; UK Petroleum Act, 1998), is seen as a particular concern owing to the artificial reef effect and connectivity occurring between structures being removed (Fowler et al., 2018). Over the next 30 years, it is expected that around 500 installations will be decommissioned (HM Government et al., 2011). There are different options for the decommissioning of energy structures. Complete removal may be the default option though other options, including leaving in situ, may be decided upon under health- and safety-based derogations considered for platforms of a certain size and specification, or if evidence suggests that the platform provides benefit to the marine environment (Fowler et al., 2018; OSPAR, 1998). Evidently, spatial changes will occur due to hard structures being removed, relocated or installed across the North Sea for years to come. Therefore, consideration of the interrelationship between hard structures and environmental effects is crucial for marine management into the future, and integral to the MSP ethos. However, a lack of clear understanding of the impacts of offshore structures, including with respect to marine connectivity, means their consideration is often excluded from the marine spatial planning process (Gill et al., 2018).

A lack of empirical data presents a significant challenge in understanding marine connectivity. However, particle tracking models, which incorporate hydrodynamics and the biological behaviour of pelagic larvae, have been used to provide estimates of movement and connectivity via pelagic larval dispersal (Bray et al., 2017; Fox, Mccloghrie, Young, & Nash, 2006; Lacroix, Maes, Bolle, & Volckaert, 2013; MacLeod & Harvey, 2014; van der Molen et al., 2015, 2018). In addition, although traditionally associated with social science, computer science and physics, social network analysis (SNA) presents a promising opportunity to examine and quantify marine connectivity. Social network analysis provides a standardized statistical summary of the properties of a collection of objects (nodes) and the connections (edges) between them. It provides insight into patterns in spatial connections, in addition to the importance of nodes to local and regional connectivity, not possible from particle tracking model outputs alone. The potential for the application of graph theory, on which SNA is based, to landscape connectivity has been discussed (e.g. Urban & Keitt, 2001), with some relevant examples of its application to understanding marine connectivity also documented (e.g. Anadón, Mar Mancha-Cisneros, Best, & Gerber, 2013; Henry et al., 2018; Treml & Halpin, 2012). However, examples of the application of network analysis to understand the role of artificial hard substrate and the potential implications of oil and gas platform decommissioning to marine connectivity in the North Sea on a large spatial scale, are not known.

This study aims to evaluate the application of a SNA approach by describing the connectivity of a marine community, comprising seven species with pelagic larval and benthic adult stages, exhibiting preference for hard substrate habitat. By adjusting the network to reflect a reduction in hard substrate associated with removal of oil and gas structures, the impact of different decommissioning scenarios is investigated. The study evaluates the contribution of artificial hard substrates to the marine hard substrate network in the North Sea and the role of artificial hard substrate, in particular that associated with oil and gas platforms, in the connectivity of otherwise isolated areas of natural hard substrate. The merit of the application of social network analysis to the assessment of ecological connectivity in a changing environment, and crucially to inform marine spatial planning into the future, is discussed.

2 | MATERIALS AND METHODS

2.1 | Hard substrate

Natural substrate data were compiled primarily from the EMODnet Phase II Seabed Habitats (October 2015) 1:250,000 vector layer (http://www.emodnet.eu/seabed-habitats) using the FOLK_5cl habitat classes (Folk, 1954; Long, 2006). 'No Data' areas of the EMODnet vector layer were supplemented by data from the earlier version (June 2015) and the JNCC EUSeaMap layer (Cameron & Askew, 2011). The North Sea substrates were subset into the five broad FOLK classifications: 'mud to muddy sand', 'sand', 'coarse substrate', 'mixed sediment' and 'rock and boulders'. Georeferenced data relating to artificial hard substrates were acquired from various sources (Table S1) and processed for model input.

The spatial footprints of some artificial structures were estimated due to the absence of detailed information. For oil and gas platforms, buffers were assigned relative to their respective tonnage (<10,000 t: 100 m; 10,000–100,000 t: 200 m; >100,000 t: 500 m). Overlapping buffer zones were merged to avoid double counting the areal value of the overlap. Buffer zone values were based on industry standards for typical safety exclusion zones around various types of offshore structure. For wind turbines, 50 m buffers were assigned based on KIS-ORCA advisory safety zone for fishing vessels. Wreck data were processed based on tonnage and construction material. A reduction in size was assumed for decay due to rot and burial and estimated using a first-order (linear) approximation with a constant decay rate per object, leading to full removal after 150 years, as described in MacLeod and Harvey (2014). Wreck tonnage was assumed to be centrally located within each grid cell with a buffer zone assigned around this centre point in line with those for platforms, but with two additional categories to accommodate lower tonnage values (<100 t: 25 m; 100–1,000 t: 50 m; 1,000–10,000 t: 100 m; 10,000–100,000 t: 200 m; >100,000 t: 500 m). These buffers were used to derive a proportion of cell occupied by artificial structures. Note that for cells spanning both marine and terrestrial environments (i.e. coastal cells), the proportion of the marine area only, that comprised hard substrate, was calculated.

2.2 | Community larval dispersal

Species connectivity data were produced according to van der Molen et al. (2018). In summary, a configuration of the 3D hydrodynamic General Estuarine Transport Model (GETM) for the north-west European shelf was run for the period 2001–2010 to estimate the currents, temperature, salinity and vertical diffusivity. The results were used to force the particle tracking General Individual Transport Model (GITM). Simulations using GITM were produced for *Alcyonium digitatum* (deadman's fingers) (Linnaeus, 1758), *Echinus esculentus* (common sea urchin) (Linnaeus, 1758), *Lophelia pertusa* (cold-water coral) (Linnaeus, 1758), *Metridium senile var. dianthus* (plumose anemone) (Ellis 1768), *Mytilus edulis* (blue mussel) (Linnaeus, 1758), *Crepidula fornicata* (slipper limpet) (Linnaeus, 1758), along with Sponges (*Porifera* spp). These organisms have a pelagic larval phase during which they are advected and dispersed by ocean currents. The selected species represent taxa commonly found settled on artificial hard substrate within North east Europe and include a non-native species (*C. fornicata*) and a vulnerable species (*L. pertusa*). Information on egg and larval durations, vertical migration behaviour, and size and growth of these species was used to parameterize ‘particles’, representing dispersing pelagic larvae, within the model (Table S2).

The model's computational domain was split into 15 × 15 km cells. While the model's resolution is higher (around 5 km), the lower resolution used provided compromise with respect to available computational resource. Cells with hard substrate present were selected as the nodes in the network and functioned as both particle release and settlement sites in the model. Larval dispersal score matrices were produced from GITM outputs. These matrices contained scores representing the proportion of particles released from source nodes which settle in receiving nodes. These scores indicate connectivity, through larval dispersal, between areas of hard substrate within nodes while accounting for the period of time during which larvae are ready to settle.

Community-level larval dispersal scores between source nodes and receiver nodes were calculated, and the community-level larval dispersal score matrices created, by taking the median larval dispersal scores, averaged across years 2001–2010, for the seven marine species.

2.3 | Community establishment potential

The total proportion of the node area comprising hard substrate was used as a proxy for a community establishment potential. The oil and gas platforms which would be removed under each proposed decommissioning scenario (i.e. platforms which do not meet derogation criteria, as detailed in Table 1) were determined. The community establishment potential for each node under each decommissioning scenario was calculated. It was assumed that establishment is equally likely on all hard substrate and that the likelihood of establishment is positively and linearly correlated with the surface area of hard substrate available (Hyder, Åberg, Johnson, & Hawkins, 2001; Roughgarden, Iwasa, & Baxter, 1985). In addition, it was assumed that oil and gas platforms which do not meet the derogation criteria under each decommissioning scenario were fully removed and therefore would no longer provide hard substrate.

TABLE 1 Description of five hypothetical decommissioning scenarios

Scenario	Topsides and substructures
1. Current regulations	<10,000 tonnes removed and brought ashore for recycling >10,000 tonnes left in place Heavy concrete gravity bases, floating concrete installations and concrete anchor bases left in place
2. Derogations removed	All structures, except for concrete gravity structures and anchors, removed and brought ashore for recycling
3. Increased derogation	<4,000 tonnes removed and brought ashore for recycling >4,000 tonnes left in place Heavy concrete gravity bases, floating concrete installations and concrete anchor bases left in place
4. Full removal	All structures removed
5. Maximum substrate	Platforms in Central and Northern North Sea left in situ Structures associated with platforms in Southern North Sea removed

2.4 | Network analysis

Community-level larval dispersal score matrices were converted into edgelists. From these edgelists, seven networks with nodes connected via directed and weighted edges were created in R (version 3.3.2), using package ‘IGRAPH’ (Csárdi & Nepusz, 2006), to represent community connectivity when only natural hard substrate is present, when all hard substrate is present and under five proposed decommissioning scenarios. Network nodes represent the 15 × 15 km grid cells containing hard substrate. Network edges represent links between nodes based on community larval dispersal. The strength (or weight) of the network edge reflects both the community larval dispersal and the community establishment potential. Specifically, edge weights were calculated by adding together the community larval dispersal score between the source and receiver node and the community establishment potential score of both the source node and receiver node and dividing by the maximum possible edge weight (i.e. 3). Edge weights therefore reflected the relative, rather than absolute probability of a connection between nodes occurring. Self-loops, edges to and from the same node, were removed. For each network, key attributes were calculated and are defined in Table 2. As igraph considers edge weights to reflect distances between nodes by default, to calculate betweenness, edge weights were converted into distances (1/weight). In order to facilitate comparison of attributes between networks representing the baseline and decommissioning scenarios, nodes no

TABLE 2 Network attribute definitions

Attribute	Definition
Nodes	Entities (e.g. people, groups, organizations and, in this case, North Sea hard substrate cells) between which connections are being examined
Edges	Connections between nodes
Density	Proportion of total potential connections that are realized
Clustering	Local connectivity in terms of the proportion of nodes connected to a single node that are also connected to each other
In-degree	Number of inward connections into the node
Out-degree	Number of outward connections from the node
In-degree strength	Strength on inward connections into the node
Out-degree strength	Strength of outward connections from the node
Betweenness	A measure of the extent to which a node serves as a bridge along the shortest path between two nodes
Arc persistence (or common edges)	A measure of the consistency in connections between different networks
Network reach	The number of nodes reachable by following directed paths from another node

longer functioning in the network were not removed, rather the connections to and from them were removed. Network nodes and edges differentiated by their strength were visualized using spatial plots.

3 | RESULTS

3.1 | Hard substrate

A total of 640 15 × 15 km grid cells (10.9% of cells within the computational domain) contain hard substrate (either natural or artificial). The geographical location of different hard substrate types varies. Natural, wind turbine and shipwreck hard substrate coverage is predominantly limited to coastal areas, whereas oil and gas hard substrate coverage is located further offshore (Figure 1). The number of grid cells containing natural, and each type of artificial hard substrate also varies (Table 3). Ninety-eight per cent of total hard substrate area comprises natural hard substrate which is contained within only 120 cells (18.8% of all cells containing hard substrate). Only 1.4% of the total area of hard substrate comprises oil and gas platforms, spread across 325 cells, 295 of which contain no other form of hard substrate. Wrecks comprise <0.62% of the total hard substrate, spread across 303 cells.

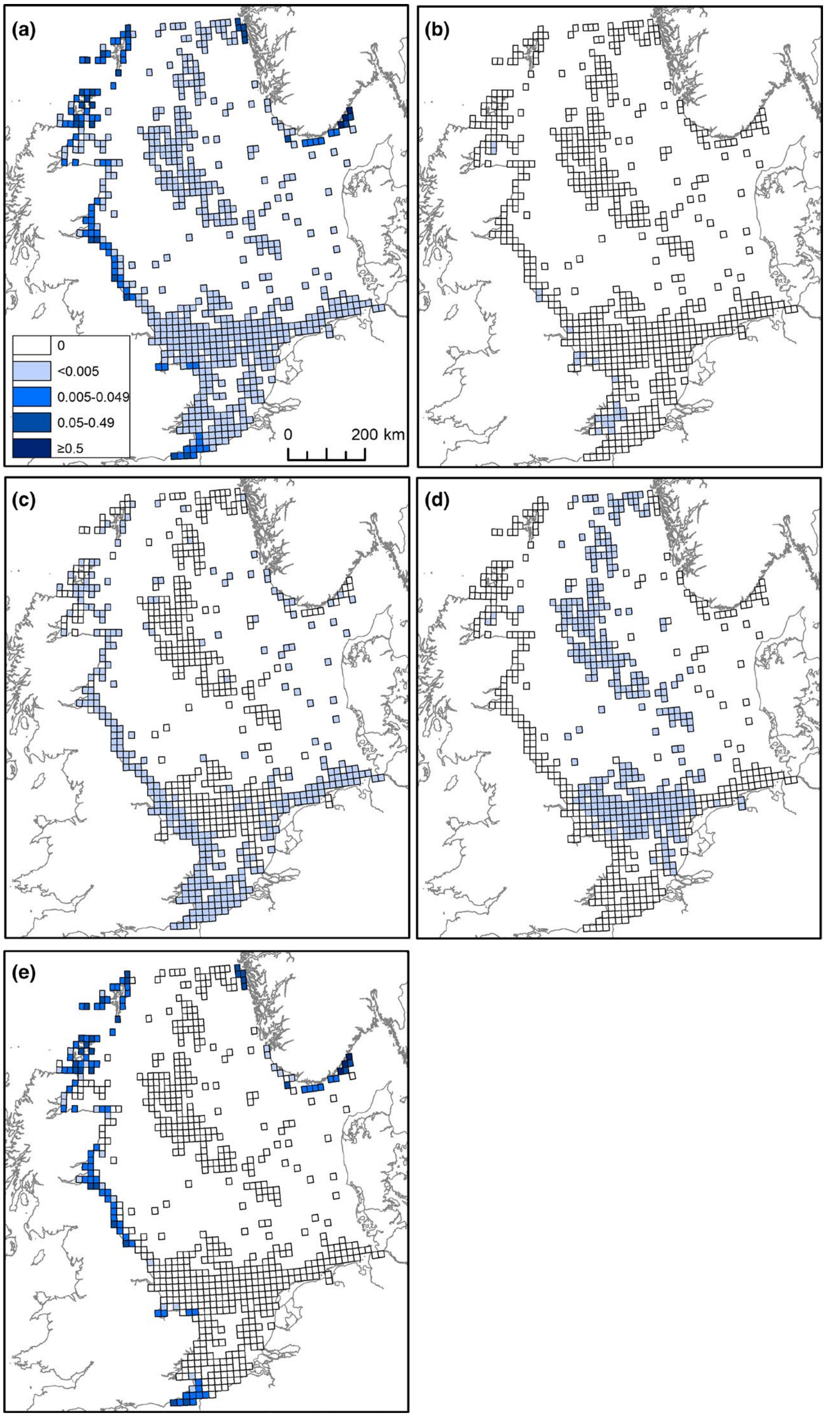

FIGURE 1 The proportion of each grid cell comprised of (a) total hard substrate, (b) wind turbine hard substrate, (c) ship wreck hard substrate, (d) oil and gas hard substrate and (e) total hard substrate

TABLE 3 Hard substrate coverage under the baseline and each decommissioning scenario (DS)

Hard substrate		Scenario	No. of cells present within	Max proportion cell coverage	Proportion of total hard substrate coverage
Natural	Rock and boulders	Baseline	120	0.72	0.98
Artificial	Wind turbines	Baseline	22	0.0043	0.0024
	Wrecks	Baseline	303	0.0011	0.0062
	Oil and gas platform	Baseline	325	0.0039	0.014
		DS1	39	0.0023	0.0031
		DS2	13	0.0026	0.0020
		DS3	85	0.0026	0.0041
		DS4	0	0	
		DS5	168	0.0039	0.010

Note: Note that min and proportion cell coverage is zero for all hard substrate types across all scenarios.

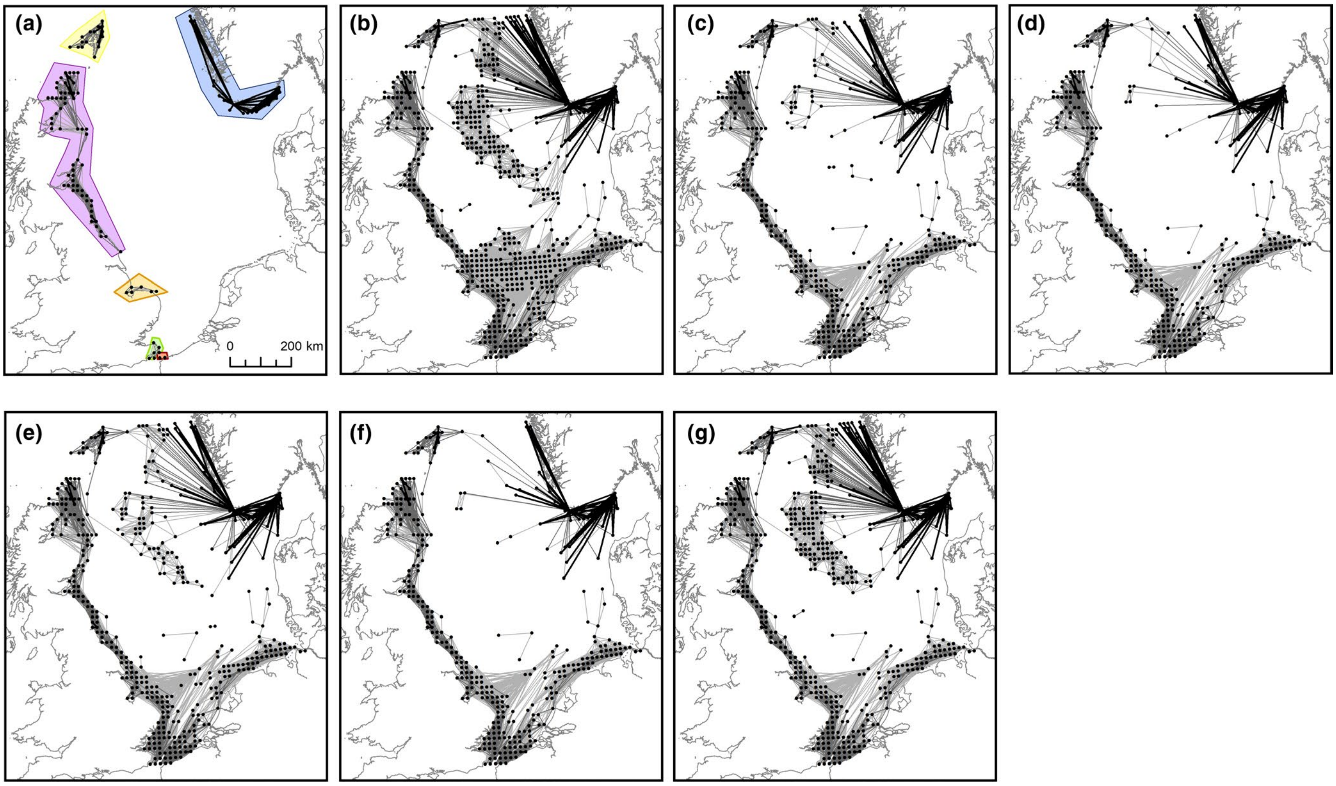

FIGURE 2 Spatial representation of the connectivity networks reflecting the natural hard substrate only, baseline scenario and decommissioning scenario 1–5 (a–g, respectively). Polygons of different colours enclose connected nodes of the natural hard substrate network

The remaining and smallest proportion of total hard substrate (<0.24%) comprises wind turbines and is spread across only 22 cells.

Reduction in hard substrate resulting from decommissioning is dependent on the specific scenario. The greatest reduction is seen under decommissioning scenario 4, while the least reduction is seen under decommissioning scenario 5. Given the location of oil and gas platforms, hard substrate coverage reduces most, and in many cases is lost, in the centrally located grid cells under decommissioning scenarios 1–4, although under decommissioning scenario 5, hard substrate coverage is reduced in southern central areas only.

3.2 | Network analysis

The natural hard substrate-only network consists of 112 nodes connected by 489 edges. The network comprises 6 discrete clusters ranging in size from between 61 to 2 connected nodes.

The clusters are geographically distinct. The largest cluster of connected natural hard substrate (61 nodes) is located off the east coast of the UK. Although comprising fewer nodes (22), the most strongly connected cluster of natural hard substrate nodes is located off the coast of Norway. Smaller clusters of 16, 6, 6 and 2 connected nodes are located around the Shetland Islands, the north coast of East Anglia, the south east tip of England and the north coast of France respectively (Figure 2). Connectivity is low in the natural hard substrate network. For example, <4% of all potential connections are actually realized, indicated by a network density of only 0.039, and <60% of the nodes connected to a single node are also connected to each other, indicated by a clustering coefficient of 0.595 (Table 4). On average, each node is connected to only four other nodes, reflected by a mean degree of 4.33. Finally, an average of 14%, and a maximum of 40%, of nodes in the network are reachable along directed larval dispersal connections from a single node. The addition of nodes containing artificial hard substrate to form the complete baseline network increased the size of the network (compared to the natural hard substrate only network) by almost sixfold, to 640 nodes. Of these 640 nodes, only 5 were independent of (i.e. not connected to) other nodes. The remaining 635 nodes were connected via 7,466 edges (Table 4). Only two nodes, although connected to each other, were disconnected from the main cluster of the baseline network. These nodes contained artificial hard substrate associated with oil and gas platforms. Although comprising more nodes and edges, and spanning a much larger geographical extent compared to the natural hard substrate only network, overall connectivity was less as indicated by a lower density and clustering coefficient. However, in comparison to the

TABLE 4 Attributes associated with networks which include only natural hard substrate (Natural HS only), all hard substrate (Baseline) and hard substrate to reflect removal of oil and gas platforms under the five proposed decommissioning scenarios (DS1-DS5)

	Network						
	Natural HS only	Baseline	DS 1	DS 2	DS 3	DS 4	DS 5
Total nodes	113	640	640	640	640	640	640
Unconnected/removed nodes	0	5	265	292	221	300	138
Clusters	6	2	4	2	3	2	3
Edges	489	7,466	3,245	3,132	3,595	3,097	4,814
Density	0.039	0.018	0.008	0.008	0.009	0.008	0.012
Clustering coefficient	0.595	0.519	0.565	0.573	0.561	0.576	0.558
Assortativity	0.008	0.168	−0.016	0.006	−0.008	0.032	−0.141
Degree mean	4.327	11.666	5.070	4.893	5.617	4.839	7.522
In-degree median	4	10	0	0	3	0	6
In-degree min	0	0	0	0	0	0	0
In-degree max	21	116	64	52	76	46	115
Out-degree median	4	11	2	1	4	1	7
Out-degree min	0	0	0	0	0	0	0
Out-degree max	14	34	26	26	26	25	25
Degree strength mean	0.216	0.118	0.085	0.083	0.089	0.083	0.101
In-degree strength median	0.091	0.059	0	0	0.012	0	0.034
In-degree strength min	0	0	0	0	0	0	0
In-degree strength max	4.575	9.848	7.097	6.511	7.689	6.212	9.841
Out-degree strength median	0.122	0.080	0.021	0.010	0.034	0.007	0.065
Out-degree strength min	0	0	0	0	0	0	0
Out-degree strength max	2.178	2.178	2.178	2.178	2.178	2.178	2.178
Betweenness mean	44.106	1,174.078	425.688	421.936	446.772	417.030	547.322
Betweenness median	0	87.5	0	0	0	0	2.5
Betweenness min	0	0	0	0	0	0	0
Betweenness max	815	24,957	15,168	14,943	15,390	14,799	15,063
Reach min	0	0	0	0	0	0	0
Reach median	10	132	5	1	12	1	48
Reach mean	16.81	172.83	56.75	55.59	61.54	54.85	82.07
Reach max	45	503	246	244	292	243	366

natural hard substrate-only network, a much greater proportion of nodes in the baseline network were reachable along directed paths, reflected by a mean and maximum network reach equating to 27% and 79% of all nodes respectively.

The addition of nodes containing artificial hard substrate into the network resulted in connectivity (although in many cases weak) between the otherwise isolated clusters of nodes containing natural hard substrate only. As such, the number of inward connections (in-degree), and their strength (in-degree strength), into nodes containing natural hard substrate only, increased with the addition of artificial hard substrate. For example, the median in-degree and median in-degree strength of natural hard substrate nodes increased from 4 to 6 and from 0.091 to 0.105, respectively, with the addition of artificial hard substrate. Of the nodes in the baseline network whose betweenness centrality score was in the top 100, and therefore frequently act as a bridge between other nodes, 47% contain artificial hard substrate associated with oil and gas platforms.

Removal of nodes from the network according to proposed decommissioning scenarios impact the size of the network, although the relative change, compared to the baseline scenario, is dependent on the specific decommissioning scenario. The largest reduction in the number of connected nodes and edges is seen under decommissioning scenario 2 and decommissioning scenario 4. For example, under decommissioning scenario 4, the number of nodes and edges reduce by 46% and 58% compared to the baseline network. The least impact on network size is seen under DS5 where the number of nodes and edges reduce by only 35% and 21% compared to the baseline network. Reflecting the loss of functioning nodes under decommissioning, a smaller proportion of realized connections (network density), reduced average node connectivity (both in terms of degree and strength) and increased clustering (global clustering coefficient) is seen for networks based on decommissioning scenarios relative to the baseline. While the maximum in-degree strength of a single node also reduced under decommissioning scenarios compared to the baseline, the maximum out-degree strength did not, thereby indicating that the node with the greatest outward connectivity strength is not removed under any of the decommissioning scenarios. The mean betweenness centrality decreases for networks reflecting each decommissioning scenario compared to the baseline network, indicating that nodes in the network bridge connections between other nodes less frequently, and therefore on average are less integral to connectivity across the network as a whole. The number of nodes reachable following direct paths (i.e. the network reach) reduces markedly under decommissioning. For example, under decommissioning scenario 4 a 68% reduction in the mean and 52% reduction in the max network reach compared to the baseline network is seen. Given that oil and gas platforms are located offshore, network nodes are generally reduced in number in the central region of the North Sea under decommissioning strategies (although for decommissioning scenario 5, only Southern Central nodes are removed).

Under decommissioning scenario 2 and decommissioning scenario 4 one cluster of three nodes exists in addition to the main network cluster. Under decommissioning scenario 3 and decommissioning scenario 5, clusters of three and two nodes were present in addition to the main network cluster. Under decommissioning scenario 1, eight nodes forming two clusters of three nodes and one cluster of two nodes were disconnected from the main network. Nodes forming these small clusters contained artificial hard substrate associated with oil and gas platforms and wrecks. Despite loss of nodes, representative of the removal of oil and gas platforms under the different proposed decommissioning scenarios, all nodes containing only natural hard substrate remain connected to the main network cluster of the decommissioning scenario networks. However, evidenced by a reduction in in-degree, connections into natural hard substrate nodes are reduced as a result of decommissioning.

4 | DISCUSSION

Connectivity is crucial to a species' distribution, persistence and productivity (Vasudev, Fletcher, Goswami, & Krishnadas, 2015). It is therefore an important consideration in current and future MSP, in which anthropogenic activities are managed to ensure a sustainable marine environment promoting healthy, functioning marine ecosystems and protected marine habitats and species (Ehler & Douvere, 2009). However, despite its importance, understanding of marine connectivity and its consideration in MSP, and marine policy decision making, remains limited (Gill et al., 2018). At a time when balancing the protection of the marine environment alongside the human pressures exerted on it is becoming ever more challenging, such knowledge gaps clearly require urgent attention.

Connectivity is difficult to evaluate and, as such, connectivity data remain limited. Connectivity can be inferred based on larval origins and dispersal pathways using genetic or geochemical markers (Cowen & Sponaugle, 2009; Levin, 2006). However, generation of connectivity data using numerical models which incorporate both physical (i.e. hydrodynamic) and biological processes, as used here, is more cost-effective, and, therefore, increasing (Hilario et al., 2015). The contribution and application of such data to marine management decisions does, however, rely on their accessibility and interpretability. This study demonstrates the role of SNA in this context. By providing a transparent, robust and standardized approach, SNA provides a means by which connectivity data can be translated into more useful and interpretable outputs.

Specifically, this study demonstrates the application of SNA to examine and quantify connectivity between areas of hard substrate in the North Sea. Creating networks to reflect connectivity with and without artificial hard substrate, and based on hypothetical oil and gas decommissioning scenarios, the approach provides general understanding of the structure, strength and extent of connectivity, insight into the contribution of artificial hard substrate to connectivity between areas of natural hard substrate, the contribution of particular nodes to overall connectivity and importantly, the potential impact of removal of artificial substrate on the structure and function of the network. Crucially, the quantitative outputs produced can be used to compare and contrast how different scenarios, for example, representing different installation and/or decommissioning options, impact marine connectivity at both small and large spatial scales.

In particular, this study highlights that artificial structures, while representing only a relatively small proportion of total hard substrate, do provide hard substrate in locations where natural hard substrate is absent, for example, in the central offshore areas of the North Sea. Artificial hard substrate, therefore, not only contributes additional hard areas but perhaps more crucially, provides 'stepping stones' by bridging gaps (Bishop et al., 2017). Such stepping stones facilitate connectivity between otherwise fragmented clusters of natural hard substrate, allowing movement of individuals and species over a larger area, minimizing risk of extinctions in isolated areas and maintaining genetic diversity within populations. Our results also highlight that decommissioning results in the removal of key geographically clustered bridging regions of the connectivity network, for example, in the central North Sea. Furthermore, outputs from the SNA undertaken indicate that decommissioning of oil and gas platforms could result in up to a 60% reduction in hard substrate community connectivity. Reduced substrate and community connectivity resulting from decommissioning may lead to lower abundance, a reduction in gene flow between populations and, if population sizes are low, an increased risk of extinction (Baguette, Blanchet, Legrand, Stevens, & Turlure, 2013 and references therein). In the context of vulnerable or protected species, these implications are clearly negative. However, when considering invasive species, whose introduction and spread may be facilitated by artificial hard substrate (Adams, Miller, Aleynik, & Burrows, 2014; Airoldi, Turon, Perkol-Finkel, & Rius, 2015; Bulleri & Airoldi, 2005; Mangano, Ape, & Mirto, 2019; Mineur et al., 2012), decommissioning can be seen as positive, acting to reduce abundance and connectivity of communities of these species thereby limiting and/or slowing down their dispersal.

While connectivity is important, its consideration in a broader context is required. For example, decommissioning may have social and economic impacts. Platforms and structures create obstacles in the marine environment, with a ban on fishing within 500 m of oil and gas platforms (UK Petroleum Act, 1998), so that their decommissioning and removal may enable increased access by commercial and recreational vessels. However, any such advantage may be offset by a reduction in fishing yields and profits as a consequence of reduced fish habitat and connectivity (Claisse et al., 2015). Implications of oil and gas decommissioning should also be considered in light of subsequent changes to the marine environment. For example, if there are plans for installation of offshore wind turbines, around which are similar fishing bans, in close proximity to platforms undergoing decommissioning, increased vessel access will be short lived.

Seven species, with life-history traits representative of those most likely to inhabit and disperse between hard substrate, were selected to represent a marine hard substrate community. Environmental factors such as temperature and salinity impact the distribution of these species throughout the North Sea (e.g. Reiss et al., 2010; Smyth & Elliott, 2016). In addition, factors such as the depth, type of hard substrate and space availability may influence the abundance and composition of communities found on hard substrate (Consoli et al., 2018; Wilhelmsson & Malm, 2008). While the seven species used here to represent a community have been recorded in the North Sea, a lack of routine and widespread monitoring for these species mean their specific distribution and spatial abundance is uncertain. In this study, we assume that these seven species can occur on, and disperse between, all areas of natural and artificial hard substrate, and that hard substrate associated with oil and gas platforms is completely removed when the platforms are decommissioned. These assumptions may result in an overestimation of the spatial extent and connectivity of the community and the scale of impact of decommissioning. However, the networks created may be considered maximum potential networks to aid understanding of any communities made up of species with similar life-history traits.

Particle tracking model outputs reflect both hydrodynamics and species biological traits. Larval duration determines the length of time and consequently the distance over which connections between hard substrates can be made, with differences in connectivity between species therefore expected. Although outside the scope of this work, and requiring accurate species distribution data for the North Sea, future examination of connectivity at the species level using the approach illustrated in this study will provide more insight into the implications of decommissioning of hard structures for particular species.

The networks developed in this study illustrate connectivity between hard substrate by an important mechanism, larval dispersal. Additional connectivity mechanisms may, in isolation or combined with larval dispersal, provide connectivity. Quantification and inclusion of such mechanisms into a connectivity network framework present a future opportunity to further understand community connectivity within the North Sea and the role of artificial hard substrate. Evidence suggests that temperature may be negatively correlated with the duration and dispersal of the larvae of marine organisms (O'Connor et al., 2007). Coupled with its impact on ocean circulation patterns (Wakelin, Artioli, Butenschön, Allen, & Holt, 2015), sea temperatures associated with climate change are likely to influence connectivity and community structure, with potential implications for the resilience of communities to removal of artificial hard substrate. SNA using data from larval dispersal models applied under climate change scenarios will provide further insight.

This work demonstrates that social network analysis, coupled with other modelling approaches, such as particle tracking models, can provide a valuable insight into marine connectivity over large geographical and temporal scales. In this study, social network analysis has been used to quantify the potential impact of decommissioning on ecological connectivity via larval dispersal between areas of the North Sea. However, there are likely many opportunities for the application of such an approach in the context of marine spatial planning. For example, social network analysis may be used to facilitate the understanding of the implications of an offshore wind farm layout and spatial separation on marine connectivity and the connectivity between populations of mobile species whose abundance is linked to artificial structures (Wilhelmsson et al., 2006). Furthermore, social network analysis may be applied to the design of MPAs, improving consideration of connectivity which is often lacking or geographically biased (Balbar & Metaxas, 2019), and enabling their optimal and successful placement. Providing transparent and standardized outputs, the application of social network analysis facilitates understanding across multiple disciplines including scientists and policymakers, thereby strengthening the science–policy nexus. As such it provides a promising tool to aid the marine spatial planning process and, a crucial step forward in light of increasing reliance on offshore energy, to address the current lack of thorough consideration of the role of offshore platforms in relation to marine connectivity.

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AUTHORS' CONTRIBUTIONS

N.T. and K.H. and H.T. conceived the ideas and designed the methodology; J.Vd.M. and L.G. generated connectivity data; P.P. sourced and analysed hard substrate data, H.T. conducted the network analysis and led the writing of the manuscript. K.H. secured funding for and led the work. All authors contributed to drafts and gave final approval for publication.

DATA AVAILABILITY STATEMENT

Data available via the Cefas Data Hub www.cefas.co.uk/cefas-data-hub. DOIs: https://doi.org/10.14466/CefasDataHub.50 (Posen, Hyder, & Lynam, 2018a); https://doi.org/10.14466/CefasDataHub.51 (Posen, Hyder, & Lynam, 2018b); https://doi.org/10.14466/CefasDataHub.52 (Posen, Hyder, & Lynam, 2018c); https://doi.org/10.14466/CefasDataHub.88 (van der Molen, Garcia, Tidbury, & Hyder, 2019).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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